Fermi National Accelerator Laboratory

MPI–PAE/PTh 38/87
FERMILAB-CONF-87/97-T
June 1987

Isoscalar Weak Vector Bosons at e^+e^--Colliders in the TeV Region**

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ABSTRACT

Many models with a composite structure of the weak interactions predict the existence of isoscalar weak vector bosons Y or Y_L which couple to the weak hypercharge current, or its lefthanded part. We discuss the production signatures of such particles at e^+e^--colliders with a center-of-mass energy in the TeV region and present possible limits on their mass from virtual effects in $e^+e^- \to \mu^+\mu^-$.

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** To appear in the Proceedings of the Workshop on "Physics at Future Accelerators", La Thuile (Val d'Aosta) and CERN, 7-13 January 1987

ISOSCALAR WEAK VECTOR BOSONS AT e^+e^--COLLIDERS IN THE TeV REGION

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Abstract

Many models with a composite structure of the weak interactions predict the existence of isoscalar weak vector bosons Y or Y_L which couple to the weak hypercharge current, or its lefthanded part. We discuss the production signatures of such particles at e^+e^--colliders with a center-of-mass energy in the TeV region and present possible limits on their mass from virtual effects in $e^+e^- \rightarrow \mu^+\mu^-$.

Probing the full dynamics of the electroweak theory [1] and searching for nonstandard effects are some of the main physics goals for experiments at the CERN Linear Collider (CLIC) [2] and the LHC [3]. Many models which go beyond the standard $SU(2)_L \; x \; U(1)_Y$ gauge theory, like superstring inspired models [4] or models with a composite structure of the weak interactions [5], predict additional heavy neutral vector bosons. In the latter one it is natural to expect excited partners of the W- and Z-bosons [6]. The most likely further composite ground state vector boson is an isoscalar Y- or Y_L-boson which is coupled to the weak hypercharge current, or its lefthanded part. A Y_L-type boson for example is predicted in the strongly coupled standard model [7]. Since the substructure scale Λ_H of the underlying preon theory is related to the Fermi constant G_F of the weak interactions in models with composite W- and Z-bosons, the $Y(Y_L)$-mass M_Y should be at most of the order of 1 TeV.

The strongest present-day limits on M_Y come from low-energy neutral current experiments and give [8]

$$M_Y > 370 \; GeV \quad . \tag{1}$$

If no deviations from the standard model were to be found, precision experiments at LEPI/SLC should yield lower bounds in the $500 - 600 \; GeV$ range [8], while LEPII (without initial state polarization) should be able to push the limit on M_Y up to $700 - 900 \; GeV$ [8].

In order to produce Y or Y_L, if they exist, one either needs a multi-TeV hadron-hadron collider like the LHC or a high luminosity ($\mathcal{L} \geq 10^{33} \; cm^{-2}s^{-1}$) e^+e^--collider with with a center-of-mass energy in the TeV-range such as CLIC. Because M_Y can a priori vary over a wide range, the LHC is likely to be a suitable machine to discover an isoscalar weak vector boson in its leptonic decay modes up to $Y(Y_L)$-masses of several TeV, in much the same way as the CERN $p\bar{p}$ collider was for the Z-boson. CLIC, on the other hand, may be uniquely suited for a detailed study of Y and Y_L, provided that M_Y is less than the center-of-mass energy E_{cm}, which currently is projected to be $\sim 2 \; TeV$.

In the following we focus on the e^+e^- option and discuss resonance production of isoscalar vector bosons at CLIC energies. In order to make our paper more generally useful, we also give the scaling laws necessary to calculate the production rates for different values of E_{cm}. Finally, we consider virtual $Y(Y_L)$-effects in $e^+e^- \rightarrow \mu^+\mu^-$ and derive lower limits on M_Y which one could hope to reach if the standard model were to agree with the experimental results at CLIC. Production of $Y(Y_L)$-bosons at the LHC will be considered in a separate contribution to this Workshop [9] where we also sketch our model and set out its couplings in an appendix.

Since $\mu^+\mu^-$ and W^+W^- are expected to be the most prominent final states to be studied at TeV e^+e^--colliders, we consider $Y(Y_L)$-resonance production in these two particular channels. In Fig. 1 we

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show the cross-section for $e^+e^- \to \mu^+\mu^-$ versus the center-of-mass energy $\sqrt{s}$ in presence of a $Y(Y_L)$-boson

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{s}{48\pi} \sum_{h_e, h_\mu} \mid F(h_e, h_\mu) \mid^2 \tag{2}$$

for $M_Y = 2\ TeV$ and various values of λ_Y^2 which measures the mixing strength of the $Y(Y_L)$ with the photon ($g_Y = e/\lambda_Y$, see [9] in these proceedings). Curves of similar shape are also obtained for different values of M_Y. In Eq. (2)

$$\begin{aligned} F(h_e, h_\mu) = \frac{e^2}{s} + \frac{1}{4}\, \frac{(V_{Z\mu}^{Y(L)} - h_\mu A_{Z\mu}^{Y(L)})(V_{Ze}^{Y(L)} - h_e A_{Ze}^{Y(L)})}{s - M_Z^2 + iM_Z\Gamma_Z} \\ + \frac{1}{4}\, \frac{(V_{Y_{(L)}\mu} - h_\mu A_{Y_{(L)}\mu})(V_{Y_{(L)}e} - h_e A_{Y_{(L)}e})}{s - M_Y^2 + iM_Y\Gamma_Y}\ , \end{aligned} \tag{3}$$

e is the electric charge unit, Γ_i, $i = Y_{(L)}, Z$ are the widths of $Y(Y_L)$ and the Z-boson and $h_{e,\mu} = \pm 1$ are the helicities of e and μ, respectively. The V's and A's are the vector and axial vector coupling constants derived from an effective Lagrangian of dimension four, using W- and $Y(Y_L)$-dominance [10]. They are listed in the appendix of ref. [9] (see also ref. [8]). Since we have neglected higher dimensional terms in the effective Lagrangian, Eqs. (2) and (3) are only valid for $\sqrt{s}$ values not much larger than M_Y. From Fig. 1 we observe that the $Y(Y_L)$-boson is signalled by a huge resonance peak centered at $\sqrt{s} = M_Y$. The width Γ_Y varies significantly with λ_Y^2 and for small values of the mixing parameter the $Y(Y_L)$ is a rather broad resonance. This can be easily understood by noting that, for small λ_Y^2, $V_{Y_{(L)}}$ and $A_{Y_{(L)}}$ are proportional to (e/λ_Y). On the other hand, since the branching ratio for the decay $Y(Y_L) \to \mu^+\mu^-$, $B(Y(Y_L) \to \mu^+\mu^-)$, is almost independent of λ_Y^2 ($B(Y(Y_L) \to \mu^+\mu^-) \approx 12...12.5$ % for $\lambda_Y^2 \leq 0.5$ [11]), the cross-section at the peak ($\sigma_{pt} = 4\pi\alpha^2/3s$)

$$R_{max} = \sigma(e^+e^- \to \mu^+\mu^-; \sqrt{s} = M_Y)/\sigma_{pt} \approx \frac{9}{\alpha^2}[B(Y(Y_L) \to \mu^+\mu^-)]^2 + 1 \tag{4}$$

changes only very little with λ_Y^2. The values of R_{max} and Γ_Y for the parameters of Figs. 1 are summarized in Table 1.

TABLE 1

λ_Y^2	R_{max}	Γ_Y $[GeV]$
0.05	2204 (2254)	498 (100)
0.10	2203 (2247)	232 (50)
0.26	2192 (2193)	69 (28)
0.50	2036 (2136)	20 (55)

Expected $e^+e^- \to \mu^+\mu^-$ cross-sections in units of σ_{pt} at the $Y(Y_L)$-peak (R_{max}) and the width of the $Y(Y_L)$ for various values of λ_Y^2. Numbers in brackets apply in the Y_L-case. The $Y(Y_L)$-mass is 2 TeV.

The large enhancement of the cross-section at $\sqrt{s} = M_Y$ may, however, be reduced if the accelerator beam energy spread δE is much larger than Γ_Y, e.g. due to effects such as beamstrahlung which is expected not to be negligible at linear e^+e^--colliders with a E_{cm} in the TeV range [2, 12]. Taking the beam spread to be Gaussian, the value of R_{max} would be approximately reduced by a factor

$$F \approx \sqrt{\frac{\pi}{8}}\, \frac{\Gamma_Y}{\delta E}\ . \tag{5}$$

In the case of the $Y(Y_L)$-boson this means that if $\delta E/E = 1$ % the cross-section would remain practically unaffected, whereas for $\delta E/E = 5$ % the peak value of σ would be reduced by up to a factor of ~ 8 for $\lambda_Y^2 \leq 0.5$.

At CLIC with $E_{cm} = 2\ TeV$, a luminosity of $\mathcal{L} = 10^{33}\ cm^{-2}s^{-1}$ and a beam energy spread of 1 %, one, thus, should hope to accumulate of the order of $(1.8 - 2.0) \cdot 10^6$ decays of a $Y(Y_L)$-boson with

$M_Y = E_{cm}$ into $\mu^+\mu^-$ per "year" ($\hat{=}10^7\ s$), depending on the value of λ_Y^2. Even with $\delta E/E = 5\ \%$ one could expect at least $2 \cdot 10^6$ events. On the other hand, only about 220 muon pairs are produced in the standard model at $\sqrt{s} = 2\ TeV$ with the same integrated luminosity so that CLIC would be a true $Y(Y_L)$ factory, in much the same way as LEPI/SLC is for the Z-boson. Since it is quite likely that the mass of the $Y(Y_L)$ is smaller than $2\ TeV$ it is useful to display how the number of muon pairs $N_{\mu\mu}$ at the $Y(Y_L)$-peak ($E_{cm} = M_Y$) changes with M_Y and the integrated luminosity $\int \mathcal{L}dt$. One finds

$$N_{\mu\mu}(M_Y, \int \mathcal{L}dt) \approx N_{\mu\mu}(2\ TeV,\ 10^4\ pb^{-1})\ \frac{\int \mathcal{L}dt}{10^4\ pb^{-1}}\ \frac{4\ TeV^2}{M_Y^2}\ . \tag{6}$$

$B(Y(Y_L) \to \mu^+\mu^-)$ does not enter Eq. (6) since it is almost independent of M_Y.

For non-zero λ_Y the $Y(Y_L)$-boson has a non-vanishing coupling to W-boson pairs [11] and therefore should appear as a resonance peak also in $e^+e^- \to W^+W^-$. In Fig. 2a we compare the production rate of W-pairs via $Y(Y_L)$ s-channel exchange

$$\sigma(e^+e^- \to Y_{(L)} \to W^+W^-) = \frac{\beta^3}{512\pi}\ (V_{Y_{(L)}}^2 + A_{Y_{(L)}}^2)\ g_{Y_{(L)}WW}^2\ \frac{s}{(s - M_Y^2)^2 + M_Y^2\Gamma_Y^2}\ G(s)\ , \tag{7}$$

where $g_{Y_{(L)}WW}$ is the $Y_{(L)}WW$ coupling constant ([9], these proceedings),

$$\beta = \sqrt{1 - 4\frac{m_W^2}{s}}\ , \tag{8}$$

m_W is the mass of the W-boson and

$$G(s) = 16\frac{s}{m_W^2} + \frac{2}{3}\ (\frac{s^2}{m_W^4} - 4\frac{s}{m_W^2} + 12)\ , \tag{9}$$

for a $Y(Y_L)$ of $2\ TeV$ mass and $\lambda_Y^2 = 0.1$ and 0.5 with the standard model $e^+e^- \to W^+W^-$ cross-section which in the $\sqrt{s}$ range of interest can be very well approximated by ($\sin^2\theta_W = \lambda_W^2$) [13]

$$\sigma(e^+e^- \to W^+W^-)_{SM} \approx \frac{\pi\alpha^2}{8\sin^4\theta_W}\ \frac{1}{s}\ \left(4\ln(\frac{s}{m_W^2}) - 5\right)\ . \tag{10}$$

The explicit form for $g_{Y_{(L)}WW}$ can be found in the appendix of ref. [9]. Since the $Y(Y_L)WW$ coupling is purely induced by $\gamma Y_{(L)}$ mixing, the production rate of isoscalar weak vector bosons in the W^+W^--channel depends significantly on the mixing strength λ_Y^2. For small λ_Y^2 the signal is seen to be considerably lower than the standard model background, whereas for large λ_Y^2 the background is negligible. The situation is therefore quite similar to the one encountered in $pp/p\bar{p} \to W^+W^-$ [11]. In trying to reduce the standard model background for small values of λ_Y^2 it is useful to recall that the $e^+e^- \to W^+W^-$ cross-section is dominated by the neutrino t-channel exchange diagram [13]. The differential cross-section $d\sigma_{SM}/d\cos\theta$, θ being the angle between the e^- and the W^-, is strongly peaked in almost forward direction resulting from the strong production of two transversely polarized W's. Since the differential cross-section for $Y(Y_L)$ follows a distribution proportional to $1 - \cos^2\theta$, a suitable cut in $|\cos\theta|$ will strongly reduce the background, whereas the $Y(Y_L)$ signal will remain practically unaffected. This is illustrated by the lower dotted line in Fig. 2a which represents the standard model $e^+e^- \to W^+W^-$ production rate for $|\cos\theta| \leq 0.8$; it is about one order of magnitude smaller than the cross-section for the full $\cos\theta$ range. The $Y(Y_L)$-signal, on the other hand, is only reduced by $\sim 6\ \%$.

The enhancement of the $Y(Y_L)$ resonance peak for small λ_Y^2 by requiring $|\cos\theta| \leq 0.8$ is made more transparent in Fig. 2b where we show the total $e^+e^- \to W^+W^-$ cross-section for a Y_L-boson of $2\ TeV$ mass and $\lambda_Y^2 = 0.1$ (i.e. including all interference terms) both with and without the cut on $|\cos\theta|$. Results very similar to the ones displayed in Fig. 2 are also obtained if M_Y differs from the value used there. A more detailed analysis of the signatures of isoscalar weak vector bosons in W pair production will be given elsewhere [14].

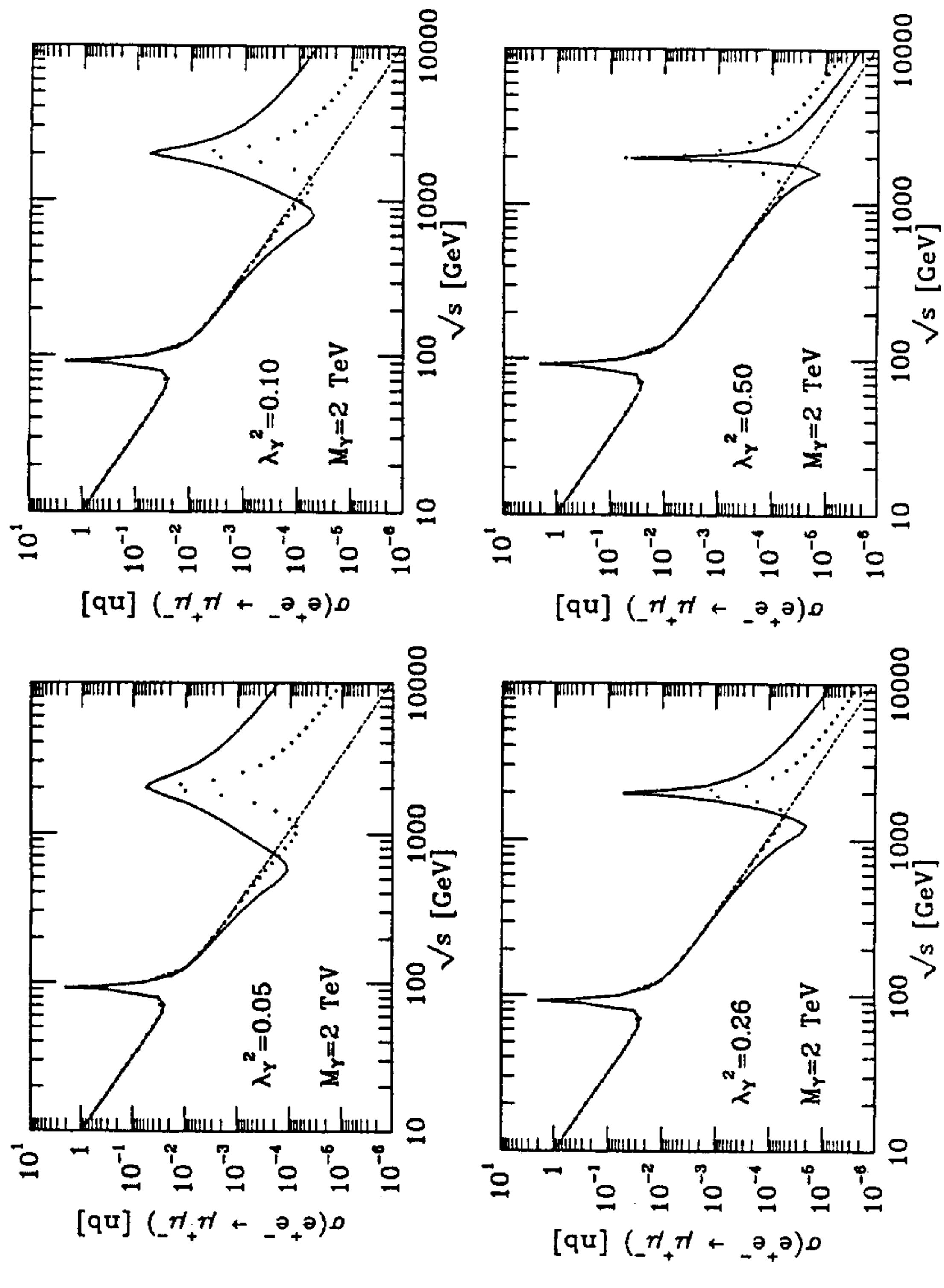

Fig. 1: The $e^+e^- \to \mu^+\mu^-$ cross-section versus $\sqrt{s}$ in presence of an isoscalar vector boson Y (solid lines) and Y_L (dotted lines) for $M_Y = 2$ TeV and various values of the $\gamma Y_{(L)}$ mixing parameter λ_Y^2. The dashed curve represents the standard model prediction.

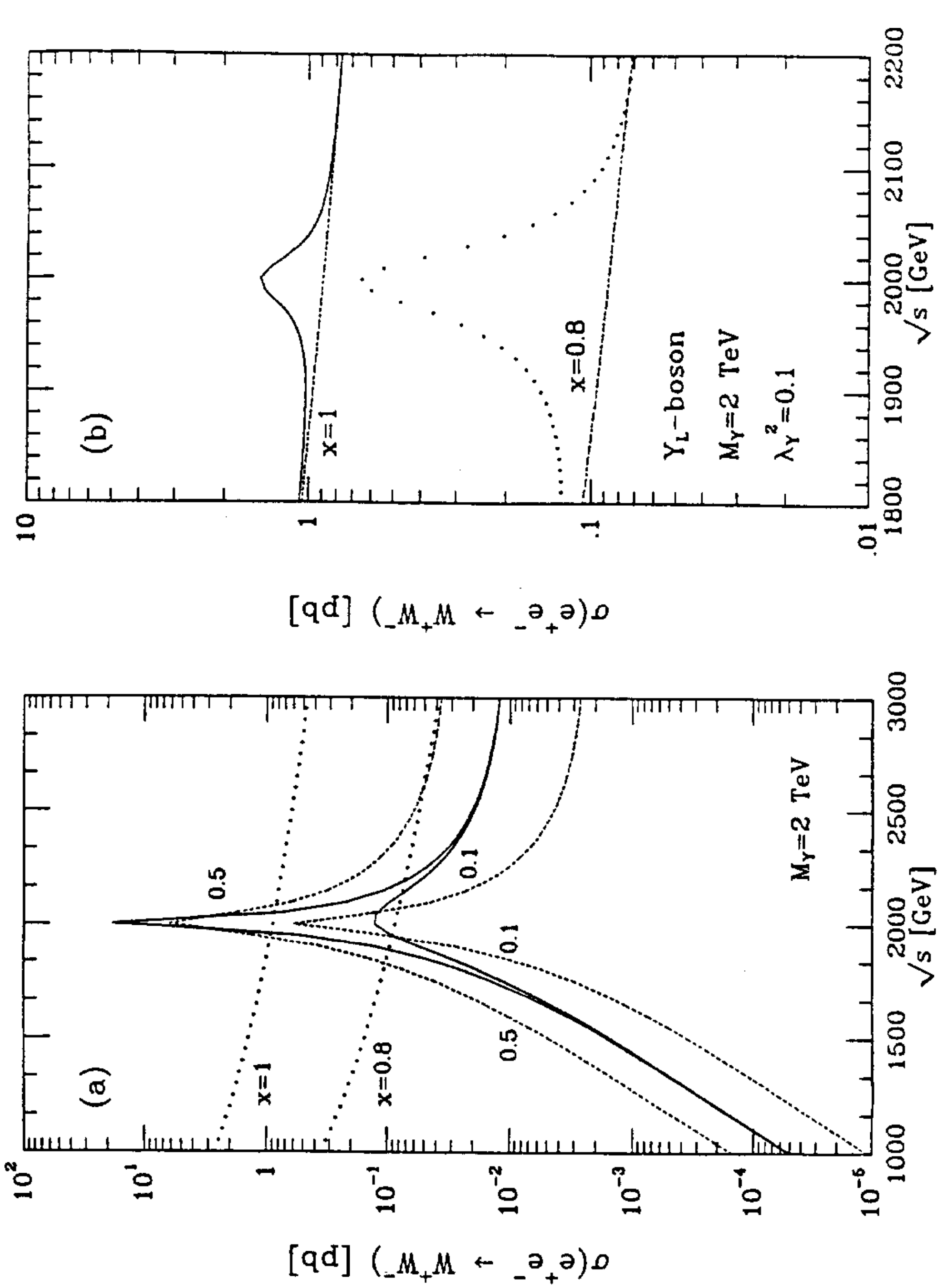

Fig. 2: a) The W-pair production cross-section versus $\sqrt{s}$ for an isoscalar vector boson Y (solid lines) and Y_L (dashed lines) of 2 TeV mass for $\lambda_Y^2 = 0.1$ and 0.5 at CLIC energies. The numbers attached to the curves denote the value of λ_Y^2. The dotted lines represent the standard model $e^+e^- \to W^+W^-$ cross-section with $|\cos\theta| \leq x$ for $x = 1$ ($\hat{=}$ total cross-section) and $x = 0.8$. θ is the angle between the beam and the W^--boson. For the W-mass we used $m_W = 80$ GeV.
b) The total $e^+e^- \to W^+W^-$ cross-section versus $\sqrt{s}$ in presence of a Y_L-boson with $M_Y = 2$ TeV and $\lambda_Y^2 = 0.1$. The solid curve gives the cross-section for the full range of $|\cos\theta| \leq 1$ and the dotted one for $|\cos\theta| \leq 0.8$. The dashed lines represent the standard model $e^+e^- \to W^+W^-$ cross-section for $|\cos\theta| \leq x$. The W-mass was chosen to be 80 GeV.

TABLE 2

x	λ_Y^2	Y-case	Y_L-case	Standard Model
1	0.1	$1.03 \cdot 10^4$	$1.49 \cdot 10^4$	$0.89 \cdot 10^4$
0.8	0.1	$2.12 \cdot 10^3$	$6.47 \cdot 10^3$	$0.87 \cdot 10^3$
1	0.2	$1.60 \cdot 10^4$	$3.25 \cdot 10^4$	$0.89 \cdot 10^4$
0.8	0.2	$0.75 \cdot 10^4$	$2.30 \cdot 10^4$	$0.09 \cdot 10^4$
1	0.5	$1.91 \cdot 10^5$	$7.27 \cdot 10^4$	$0.89 \cdot 10^4$
0.8	0.5	$1.72 \cdot 10^5$	$6.07 \cdot 10^4$	$0.09 \cdot 10^4$

Expected number of $e^+e^- \to W^+W^-$ events satisfying $|\cos\theta| \leq x$ (θ: angle between the W^- and the beam direction) at CLIC ($E_{cm} = 2$ TeV ; $\int \mathcal{L}dt = 10^4$ pb^{-1}) in the standard model and in presence of a $Y(Y_L)$-boson with $M_Y = E_{cm}$.

In Table 2 we finally list the W-pair production rate to be expected for CLIC at the $Y(Y_L)$-peak for various values of λ_Y^2. The number of $Y(Y_L)$ decays, $N_{WW}^{Y(L)}$, as well as the number of standard model events, N_{WW}^{SM}, satisfying $|\cos\theta| \leq x$, with $2m_W^4 x \ll s^2(1-x)$, scale with M_Y (respectively $\sqrt{s}$) and $\int \mathcal{L}dt$ like $N_{\mu\mu}$. If no cut on $|\cos\theta|$ is applied, one finds for N_{WW}^{SM} instead

$$N_{WW}^{SM}(\sqrt{s}, \int \mathcal{L}dt) = N_{WW}^{SM}(2\ TeV,\ 10^4\ pb^{-1})\ \frac{\int \mathcal{L}dt}{10^4\ pb^{-1}}\ \frac{0.193\ TeV^2}{s}\ \left(4\ln(\frac{s}{m_W^2}) - 5\right) \tag{11}$$

since the forward peaking of the neutrino exchange diagram introduces a term depending logarithmically on s if the full $\cos\theta$ range is considered.

The chances to observe the decay $Y(Y_L) \to W^+W^-$ in e^+e^- annihilations are much better than in hadronic collisions where a large hadronic background complicates the identification of W-pairs [15]. Given the considerable variation of $N_{WW}^{Y(L)}$ with λ_Y^2 and the large number of $Y(Y_L)$-decays expected, it should be fairly easy to determine λ_Y^2 from $e^+e^- \to W^+W^-$, or to obtain a strong upper limit on the mixing strength if no enhancement of the cross-section is observed. If $\sigma(e^+e^- \to W^+W^-;\ |\cos\theta| \leq 0.8)$ can be measured at CLIC with a combined statistical and systematical error of, say, 20 %, an upper bound of $\lambda_Y^2 < 0.035$ (0.017) can be derived in this case for a $Y(Y_L)$-boson produced at resonance. From Tables 1 and 2 we also observe that, for given λ_Y^2, Γ_Y and $N_{WW}^{Y(L)}$ are in general very different for Y and Y_L. If both quantites can be determined, it should be possible to clearly discriminate between a Y- and a Y_L-boson.

Thus far we have concentrated on the production of isoscalar weak vector bosons. If M_Y is larger than the center-of-mass energy at CLIC one has to search for virtual effects of $Y(Y_L)$. It turns out that the reaction $e^+e^- \to \mu^+\mu^-$ is the most sensitive one to indirect manifestations of such particles. Due to the in general rather large vector coupling constant $V_{Y_{(L)}}$ to charged leptons, a strong destructive interference between the photon and the $Y(Y_L)$ amplitude occurs in $\sigma(e^+e^- \to \mu^+\mu^-)$ for $\sqrt{s} < M_Y$. This is clearly visible in Fig. 1. Only in the Y_L-case for $\lambda_Y^2 \approx 0.26$, where V_{Y_L} vanishes for charged leptons [11], there is no such effect.

$Y(Y_L)$-exchange may also significantly affect the forward-backward asymmetry

$$A_{FB} = \frac{F-B}{F+B}\,, \tag{12}$$

$$F \pm B = \left[\int_0^1 \pm \int_{-1}^0\right] d\cos\theta\ \frac{d\sigma(e^+e^- \to \mu^+\mu^-)}{d\cos\theta}\,, \tag{13}$$

(θ is the angle between the μ^- and the beam direction) and, if the incident e^--beam at CLIC can be (partially) longitudinally polarized, the left-right asymmetry

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}\,, \tag{14}$$

$\sigma_{L,R}$ being the cross-sections for $e^-_{L,R} + e^+ \to \mu^+\mu^-$. A detailed analysis of the electroweak asymmetries in presence of an isoscalar weak vector boson can be found in ref. [8]. Here we would like to concentrate on the lower limits on M_Y which one could obtain from a measurement of A_{FB} and A_{LR} at $\sqrt{s} = 2\ TeV$ if experiments there agree with the standard model within the possible experimental accuracies. For an integrated luminosity of $10^4\ pb^{-1}$, corresponding to a running period of one "year" ($\hat{=}10^7\ s$) at a luminosity of $\mathcal{L} = 10^{33}\ cm^{-2}s^{-1}$, the estimated statistical error for A_{FB} is

$$\delta A_{FB}(\sqrt{s} = 2\ TeV) = 0.06 \tag{15}$$

whereas the expected accuracy in the left-right asymmetry for a 50 % longitudinally polarized electron beam is

$$\delta A_{LR}(\sqrt{s} = 2\ TeV) = 0.04\ . \tag{16}$$

If an integrated luminosity of $4 \cdot 10^4\ pb^{-1}$ could be achieved, the errors in Eqs. (16) and (17) would be a factor 2 smaller.

Our analysis proceeds in the same way as in the LEPII case [8, 16]. To determine the contours limiting the allowed region in the (λ_Y^2, M_Y) parameter space, which completely specifies the properties of $Y(Y_L)$, we also take into account that the ratio m_W/M_Z can certainly be obtained at LEPI/II with 0.2 % accuracy and - conservatively - assume that $\sigma(e^+e^- \to \mu^+\mu^-)$ can be measured with a combined statistical and systematical error of $\delta\sigma/\sigma = 20$ % at $\sqrt{s} = 2\ TeV$. From the limiting contours we then directly read off the lower bounds on M_Y. Depending on the coupling of the isoscalar vector boson, on the accuracies achieved for the electroweak asymmetries and depending on whether longitudinal polarization for the e^--beam is available or not, these lower bounds range from 2.75 to 7.0 TeV. CLIC may thus be sensitive to isoscalar weak vector bosons with masses well above the naturally expected mass range for partners of composite W- and Z-bosons.

Finally, we would like to compare our estimates for isoscalar weak vector bosons with the results for a second massive neutral gauge boson Z' appearing in some superstring inspired models [12]. Since the $Z'WW$ coupling is also purely induced by $Z' - Z$ mixing, $Y(Y_L)$ and Z' affect the $e^+e^- \to W^+W^-$ cross-section in a very similar way. Y- and Y_L-bosons differ, however, significantly from the Z' in their vector and axial vector coupling constants and, therefore, also in their production rates in $e^+e^- \to \mu^+\mu^-$. Since $B(Y(Y_L) \to \mu^+\mu^-)$ is typically a factor 2 to 20 larger than the corresponding branching ratio for the Z' [12], the expected counting rates at the resonance peak for the $Y(Y_L)$ are much bigger than for the second neutral gauge boson in superstring inspired models.

In summary, we have estimated production rates of isoscalar weak vector bosons Y and Y_L in e^+e^--collisions at CLIC energies. While the cross-section in $e^+e^- \to \mu^+\mu^-$ depends only slightly on the $\gamma Y(Y_L)$ mixing strength λ_Y, the signal in the W^+W^- channel varies strongly with λ_Y^2. For small values of the mixing parameter a cut on the angle of the outgoing W will be very helpful in removing the standard model background. Electroweak asymmetries and the cross-section in $e^+e^- \to \mu^+\mu^-$ turn out to be sensitive to $Y(Y_L)$-effects for values of M_Y as large as 7 TeV, well above the natural mass-scale for such objects.

ACKNOWLEDGEMENT

One of us (U.B.) would like to thank the Max-Kade-Foundation, New York for financial support.

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